Size and orbit dependent trends in the reflectance colors of Earth-approaching asteroids

David Rabinowitz
Jet Propulsion Laboratory, California Institute of '1'ethnology
davidr@slam.jpl.nasa.gov (818) 3544256

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Abstract

New observations show that reflectance colors of Earth-approaching asteroids depend on their sizes and orbits. Most bodies larger than -2 km have reddish colors similar to S-type asteroids. Smaller bodies, and those that may have recently migrated from the main asteroid belt, have relatively neutral spectra in the 0.5 to 0.8 μ wavelength range. These trends may result from the action of "space-weathering", which has been proposed to explain similar spectral variations apparent on the surfaces of S-type asteroids, and to explain the disparity between the colors of ordinary -chondrite meteorites and their probable parent bodies in the main belt.

Introduction

Recently, spectral observations of asteroids have been reported that identify a plausible origin for the ordinary chondrite meteorites (OCs), which are (he most *common* meteorite class. Owing to the paucity of main-belt asteroids with matching spectra [1, 2] , it had previously been a long-standing problem to explain their sources. Now Binzel et al. [3] and Hicks et al. [4] find a significant number of km-sized Earth approachers with reflectance spectra similar to OCs, and with spectra spanning the range from OCs to S-types. These small, unstable asteroids, which require a source of their own, probably represent the intermediate suppliers of the OCs. The question of their own origin, meanwhile, may be resolved by the images of (243) Ida and (951) Gaspra recorded by the Galileo spacecraft. Chapman's [S] anal yses of spectral features on Ida, and to a lesser extent on Gaspra, show that fresh surfaces exposed by recent cratering events have reflectance spectra that are different than the overal I S-type spectra characterizing the older surfaces of these two asteroids. The young surfaces have relatively deep 1-pm absorption bands and relatively flat spectra! slopes near (). S μm. The trend is such that the youngest surfaces on Ida have spectra most closely resembling OCs. Furthermore, recent laboratory experiments using laser pulses to simulate the effects of micrometeorite bombardment show that the reflectance spectra of OCs can be altered to resemble S-type asteroids [6]. Hence, it appears that some S-type asteroids have reflectnace spectra differing from OCs only because their surfaces have been altered over the ages by micrometeorite bombardment, or perhaps some other space-weathering process (e.g. solar wind particles, or radiation). It is therefore plausible that the OCs are relatively unweathered fragments of S asteroids, which arc of the spectral type that dominates the inner regions of the main belt where most Earth approaches are thought to originate [7, 8, 9].

This paper reports new spectral observations of Earth approachers in support of the weathering hypothesis. The observations arc the result of an ongoing spectral survey of Earth approaches conducted with the 24" telescope at Table Mountain Observatory (TMO) in Wrightwood CA, which is owned by the Jet Propulsion Laboratory (JPL). Opportunities to observe Earth approaches have recently increased in number, owing to upgrades to the Spacewatch search at the (University of Arizona [10], and to the start of the Near-Earth Asteroid Tracking program run jointly by JPL and (he U.S. Air Force [11]. By reserving -5 dark nights per month over a period of 6 months , and observing at times close to the discovery dates of the Earth approaches (when they are usually the nearest and brightest), the TMO survey is pushing the size range of the spectrally observed bodies down to a limiting size of several hundred mete.rs, roughly [en times smaller than previous surveys.

The resulting distribution of Earth-approacher colors shows a strong size dependence. Whereas most of the observed Earth approaches larger than -2 km have reddish reflectance colors similar to the S-type asteroids, the smaller bodies have spectra that are relatively flat near 0.5 μm. Although (he limited spectral range and low signal-to-noise ratio of the observations preclude spectral classification, it appears likely that most of the smaller Earth approaches either have neutral spectra similar to C-type asteroids, or else a spectral reflectance similar to OCs. Furthermore, there is an orbital dependence to the observed colors. The bodies with spectra most resembling S-types are sparse among the observed Earth approaches with semimajor axes, $a > 2.3$ AU. Both of these trends are to be expected if the effect of weathering increases with age, causing a change from OC-like to S-like colors. The predominance of small Earth approachers with neutral spectra may be an independent phenomenon, perhaps indicating the preferential contribution of cometary parents to the small-body population.

Observational Method

For all observations, a Tektronix CCD (512 x 512 pixels) with liquid nitrogen dewar and electronics built by Photometries (Tucson, AZ) was used at the Cassegrain focus of the TMO 24". The image scale was 0.431 arcsec per pixel. Digital images were recorded through four standard filters (B, V, R, 1 centered at 0.44, 0.S5, 0.67, and 0.81 μm, respectively) for each bright asteroid (V< 17). For fainter targets (17 < V <19), only V, R, and I images were recorded. All images were bias subtracted and flat fielded using bias frames and flat fields (filtered dome or sky images) recorded at the beginning or the end of each night. To correct for the rotational lightcurves of the observed asteroids, measurements of R were alternated with measurements of I, V, and B (typically R-I-R-V-R-B-R). For those cases with significant variations in R, color ratios (l-R, V-R, and B-R) where then determined by assuming a variation for R that was linear with the time, t, between successive observations. No observations were. separated in time by more than 12 minutes

To calibrate the resulting color magnitudes and magnitude ratios (B-V, V-R, and R-1), filtered images were also recorded for bright standards (V-9), selected from the observations of Landolt [12]. Several sets of these standards (usually three per set) were observed each night, selected so that all members of a given set had similar positions (separated by < -10, , yet widely ranging values for B-V, V-R, and R-I (spanning the spectral range of the target asteroids). By choosing several sets of standards widely spaced across the sky, ant] re-observing each set at 1 to 2 hour intervals throughout the night, the nightly airmass dependence of the transformations from instrumental to calibrated color ratios was thereby determined. Standard software (IRAF) supplied by the National Optical Astronomy Observatories was used to determine the sky-subtracted signal from each target star and asteroid.

Results and Discussion

Table 1 shows the values for V, B-V, V-R, and V-I measured for 33 Earth approaches observed August 1996 to February 1997. The observed color ratios are divided by solar values B-V = 0.665, V-R = 0.367, and V-1 = 0.705, determined by observations of solar-type stars [13]. Each asteroid's orbital elements (a, e, i, q) and absolute magnitude, H, are also shown [14]. Those asteroids for which lightcurve corrections were necessary arc marked by an asterix after their designation. The entries are ordered by increasing H. In all cases, the estimated error in the measured magnitudes is dominated by the photon noise in the subtracted sky signal, The calibration error is -0.01 magnitudes, determined from the root-mean-square deviation between the catalogue and observed magnitudes of the standards.

To illustrate the size dependence of these color observations, Figs. 1a and 1 b show V-I vs V-R for those Earth approachers with $H < 17$ (d>~2 km) and with $H \geq 17$ (d< ~2km), respectively. Large triangles represent asteroids observed only in V, R, and I. Large, filled squares represent the subset of bodies bright enough for additional observations in B. Figures 2a and 2b show B-V vs V-R for this brighter subset (for $H < 17$ and $H \geq 17$, respectively). Also plotted in each of these figures arc the color ratios for 1.4, 1.5,1.6, H6, and LL6 ordinary chondrites and for main-belt asteroids of type C, S, and D that were observed in the Eight Color Asteroid Survey (ECAS) [15]. Here, transformations from the ECAS filter set to BVRI were determined by E. Howell [13] from observations of standards in both filter sets [15, 16, 17].

Comparing Figs. 1a and 1 b, it is apparent that the Earth approaches larger and smaller than -2 km do not share the same color distribution. Most of the large bodies (10 of 14) have values for V-1 and V-R similar to the S-type asteroids in the main belt (V-R = 0.06 to 0.25, V-I = 0.06 to 0.3). Only 2 of 14 have colors in the range of C-type asteroids (V-R = -0.04 to 0.06, V-I = -0.05 to 0.06). Most of the smaller bodies (15 of 19), on the other hand, have values for V-1 and V-R that are lower than for S-type asteroids, and mom consistent with C types and OCs. Because the measurement errors are relatively large for these intrinsically fainter bodies, the shape and extent of their color distribution is not well determined. However, there arc enough observations to reveal a significant displacement in the small-body distribution toward relatively neutral, and in some cases blue, reflectance colors.

Figures 2a and 2b provide additional spectral information to help explain the size-dependent trend. As in Fig. 1a, most of the large Earth approachers (5 of 8 in Fig. 2a) have values for B-V and V-R that are consistent with S types. Only one is consistent with a C type, and two have unusual colors mostly closely resembling D types. Of the 4 smaller Earth approaches represented in Fig. 2b, however, there are two (1997 BQ anti 4947 Ninkasi) with large values for B-V (0.20±0.09 and 0.3±0.08, respectively) and with low values for V-R (0.034±0.043 and 0.048±0.028, respectively). These values are only marginally consistent with main-belt colors. They are a better match to the co1ois of the ordinary chondrites, particularly the LL6 group. Referring back to Fig. 1 b, it is apparent that this resemblance diminishes at longer wavelengths. The respective V-I values for 1997 BQ and 4947 Ninkasi (O. 104+0.061 and 0.076±0.039) are larger than expected for OCs. However, Chapman's analysis of the freshly exposed surfaces on Ida, and recent observations of Earth approachers [3, 4], show that we can expect small bodies with 1 -µm absorption bands (i.e. V-1 values) spanning the gap between S types and OCs. Hence, the size-dependent shift in the observed spectral distribution of the Earth approached-s may result, in part, from an increasing fraction of small bodies resembling OCs.

That asteroids with the color of OCS should become more prevalent with decreasing size is consistent with the prevalence of OCs among meteorites, and with the hypothesis that OCS are the unweathered fragments of larger, S-type asteroids. The effects of collisional weathering upon a small body will decrease with size because the collisional ages of asteroids also decrease with size. This argument can be made more quantitative by using a recently developed, quasi-analytic, Monte Carlo model [7] to predict the age distribution of the Earth approaches as a function of size, taking into account both their dynamical and collisional evolution. This model predicts that half the bodies with d -0.2 km have collisional ages in the range 10^6 to 10^8y, whereas 90% of the bodies with d -2.0 km are older (10^8 to 10' y). A comparable disparity in ages may be expected for the Earth approaches represented in Figs. 1 a and 1 b, as the median H values of the large and small bodies differ by 4.3, corresponding to diameter ratio of 7.2.

Figure 3 presents another aspect of the observed colors that supports the weathering scenario. The figure shows V-I vs V-R for all the Earth approaches listed in Table 1, using open and filled boxes to represent asteroids with $a < 2.3$ AU and $a \geq 2.3$ AU, respectively. Here it is apparent that the bodies with small a dominate the distribution for V-R > 0.1. All the Earth approachers with a > 2.3 AU, on the other hand, have relatively neutral colors (V-R < 0.1). But Earth approaches with a > 2.3 AU arc also likely to be relatively recent arrivals from the main belt, owing to the influence of the 3:1 commensurability resonance with Jupiter. This assertion can be verified by another application of the model described in Ref. [7]. Simulating the orbital evolution (but ignoring collisional evolution) for bodies ejected from the main belt under the influence of the 3:1 resonance and of the v6 secular resonance, the model predicts dynamical ages in the range 10* to 109 years for bodies with a < 2.3 AU, but a precipitous drop in ages for $a \geq 2.3$ AU. For a -2.5 AU, all the Earth approachers have dynamical ages in the range 10^7 to 10^8 y, comparable to the predicted collisional age for small (d -0.2 km) Earth approachers. Hence, the OC-colored Earth approaches with $a \geq 2.3$ AU may be the fresh fragments of S-type asteroids, with dynamical lifetimes that arc too short to have allowed significant weathering.

While space weathering may explain the abundance among the small Earth approaches of OC-like bodies, it does not explain the abundance of the bodies resembling C types. Because the C-typc asteroids represent a significant fraction of the main-belt population, a significant number are expected among *both* the large and small Earth approachers. Main-belt parents of the C type are not expected to preferentially supply smaller bodies. Furthermore, C-type asteroids have albedos -4 times lower than the albedos of S types (and of OCs). It follows that their limiting distance of detection (as a function of size) is smaller than for S types, so that their efficiency of detection is lower. For example, Muinonen [18] predicts a discovery completeness 3.4 times greater for bodies with d = 100m than for bodies with d = 50m in the initial years of a survey with limiting magnitude, V_{lim} = 24. These diameters correspond to the sizes of S and C type asteroids with H -24. An equivalent discovery bias can be expected for Earth approachers with 11-20, detected by current searches with V_{lim} -20. Hence, if the small bodies in Figs. 1, 2, and 4 that have colors resembling C types really are C types (or other low-albedo types), than they are under-represented by a factor -3 or more.

A possible explanation for the apparent abundance of the small, C-t ypc bodies could be the contribution of cometary fragments, most of which are known to have either neutral C-type colors, or else reddish colors at least as steep as D-type asteroids [19, 4]. Because comets arc also likely to suppl y the smal I Earth approaches by a mechanism independent of the collisional cascade active in the main belt, it is plausible that they could preferentially supply the smaller bodies. This might also explain the steep size distribution observed for Earth approaches smaller than -50 m [20]. However, previous spectral observations of these smallest Earth approaches [21, 22] show that many have unusually red spectra, inconsistent with C-types. An explanation would have to be found for a shift in the color distribution from neutral to reddish colors with a decrease in size.

Conclusions

The TMO spectroscopic survey, after 6 months of scheduled observations (yielding 10 photometric evenings), has produced significant new spectral data constraining the origin and evolution of the Earth-approaching asteroids. Although the TMO 24" is of modest aperture compared to instruments employed in previous surveys, and the resulting spectral observations do not yield unambiguous taxonomic classifications, frequent access to the telescope has enabled a sufficient number of observations to reveal significant trends in the color distribution. It is now clear that for d < ~2km and for a > 2.3 AU, there is an increase in the fraction of Earth approachers with colors that are neutral compared to S-type asteroids, closer in resemblance to C-type asteroids and also to OCS. These trends can be expected for the OC-like objects if they arc the young, unweathered fragments of significantly older, weathered S-type asteroids in the main belt. The reason that the C-type material shares a similar distribution remains unanswered, although an abundance of cometary material at small sizes may be implicated. With forthcoming increases in the discovery rate of the Earth approachers, owing to upgrades to the Spacewatch and NEAT discovery rate of the Earth approachers, owing to upgrades to the Spacewatch and NEAT programs, and to the start of the Lowell Observatory Near-Earth Object Survey, further spectral studies will delineate these spectral trends more clearly. This will be an exciting opportunity to untangle the origins of the Earth-approaching bodies and the associated meteorites.

References

[1] R. P. Binzel, S. Xu, S. J. Bus, M. F. Skrutskie, M. P. Meyer, P. Knezek, and E. S. Barker, Science 262, 1541 (1993).

[2] M, J. Gaffey, T. H. Burbine, and R. P. Binzel, Meteoritics 28, 161 (1993).

[3] R. P. Binzel, S. J. Bus, T. H. Burbine, and J. M. Sunshine, Science 273,946 (1996).

[4] M. D. Hicks, U. Fink, W. M. Grundy, "The Unusual Spectra of 15 Near-Earth asteroids and Extinct Comets", submitted to Icarus (1997).

[5] C. R. Chapman, Meteoritics and Planetary Science 31, 699 (1996).

[6] L. V. Moroz, A. V. Fizenko, L. F. Semjonova, C. M. Pieters, and N. N. Korotaeva, Icarus 122, 366 (1996).

[7] D. L. Rabinowitz, Icarus 127,33 (1997)

[8] A. Morbidelli, R. Gonczi, Ch. Froeschle, and P. Farinella, Astron. Astroph ys. 282, 955 (1994).

[9] G. W. Wetherill, Icarus 76, 1 (1988).

[10] T. Gehrels, J. D. Herron, R. Jedicke, R. S. McMillan, T. Metcalfe, J. Montani, J. Nichol, and J. V. Scotti, BAAS 28, 1081 (1996).

[11] E. F. Helin, S. H. Pravdo, K. J. Lawrence, D. L. Rabinowitz, G. V. Williams, and M. S. Keesey, BAAS 28, 1105 (1996).

[12] A. U. Landolt, Astron. J. 104,340 (1992).

[13] E. Howell, personal communication

[14] B. G. Marsden, Minor Planet Center internet web site.

[15] B. Zellner, D. J. Tholen, and E. F. Tedesco, Icarus 61, 355 (1985).

[16] E. F. Tedesco, D. J. Tholen, and B. Zellner, Astron. J. 87, 1585 (1982)

[17] A. U. Landolt, Astron. J. 88, 439 (1983).

[18] K. Muinonen, Planet. Space. Sci, in press (1997).

[19] P. R. Weissman, M. F. A'Hearn, L. A. McFadden, and H. Rickman, in Asteroids II, R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds. (University of Arizona, Tucson), p. 880-920 (1989).

[20] D. L. Rabinowitz, Astrophys. J. 407,412 (1993)

[21] D. L. Rabinowitz, T. Gehrels, J. V. Scotti, R. S. McMillan, M. L. Perry, W. Wisniewski, S. M. Larson, E. S. Howell, and B. E. A. Mueller, Nature 363, 701 (1993).

[22] D. L. Rabinowitz, in Completing the Inventory of the Solar System, T. W. Rettig and J. M. Hahn, Eds. (Astron. Soc. Pac. Conf. Ser. 107), pp. 13-28 (1996).

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TABLE 1. Magnitudes and Reflectance Colors for Earth Approachers.

(* indicates that rotational lightcurve corrections were required)

Designation	V	B-V	V-R	V-I	a (AU)	e	i(″)	q(AU)	H	Observ. Dates (UT)
4957	16.8	–	0.148(0.046)	0.200(0.063)	1.566	.219	35.01	1.223	12.2	1997 Jan. 11
4954*	16.0	0.185(0.034)	0.154(0.018)	0.184(0.029)	2.001	.448	17.47	1.105	12.5	1997 Jan. 11
1997 CZ5*	15.2	0.165(0.032)	0.089(0.018)	0.069(0.024)	2.334	.408	25.08	1.382	13.5	1997 Feb. 12
5407*	15.9	0.029(0.050)	0.149(0.030)	0.095(0.030)	1.8386	.277	11.39	1.328	13.8	1997 Feb. 14
4179	14.0	0.168(0.014)	0.100(0.015)	0.098(0.021)	2.516	.634	0.47	0.921	14.0	1997 Jan. 11
5131	17.7	–	-0.148(0.076)	-0.030(0.088)	1.486	.570	36.38	0.639	14.1	1997 Jan. 10
3122	16.3	0.292(0.056)	0.119(0.034)	0.227(0.045)	1.769	.423	22.17	1.021	14.2	1997 Jan. 10
1685′	16.3	–	0.094(0.025)	0.164(0.040)	1.367	.436	9.38	0.771	14.2	1997 Jan. 10
4197*	13.0	0.175(0.006)	0.078(0.003)	0.096(0.006)	2.297	0.773	12.18	0.521	14.5	1996 Oct. 15
3200	15.9	-0.005(0.038)	0.024(0.026)	-0.023(0.033)	1.271	0.890	22.09	0.140	14.6	1996 Oct. 16
3103′	15.8	-0.009(0.024)	0.222(0.015)	0.288(0.024)	1.406	.355	20.94	0.908	15.4	1997 Jan. 11
1996 TQ9	17.8	-0.05 (0.14)	0.184(0.094)	0.28 (0.11)	1.825	0.213	24.27	1.436	16.0	1996 Oct. 14
1996 TE11	16.6	–	-0.014(0.055)	-0.006(0.065)	2.466	0.451	24.46	1.354	16.0	1996 Oct. 17
1993 XN2	18.0	–	0.272(0.071)	0.464(0.088)	2.1181	.535	25.38	0.985	16.5	1997 Jan. 11
1997 BR	17.9	-0.02 (0.14)	0.052(0.094)	0.02 (0.12)	1.336	.306	17.23	0.928	17.0	1997 Feb. 12
5693	17.7	–	-0.013(0.049)	0.006(0.065)	1.272	.585	5.06	0.527	17.0	1997 Jan. 10
1997 CO5	17.7	–	0.056(0.073)	0.039(0.088)	2.707	.497	19.35	1.362	17.0	1997 Feb. 12
1994 PC	17.2	–	0.121(0.049)	0.183(0.069)	1.568	.317	9.46	1.071	17.0	1997 Jan. 10
1991 VH*	17.7	–	0.173(0.051)	0.193(0.085)	1.137	.144	13.92	0.973	17.0	1997 Jan. 11
1980 PA*	16.9	–	0.112(0.040)	-0.170(0.090)	1.925	.458	2.17	1.043	17.4	1997 Jan. 10
1996 TO5	18.2	–	0.03 (0.12)	0.04 (0.13)	2.168	0.484	19.33	1.119	17.5	1996 Oct. 15
1996 SK*	18.4	–	0.063(0.070)	-0.027(0.087)	2.431	0.797	1.95	0.493	17.5	1996 Oct. 14,15,16,17
1997 BQ*	17.2	0.204(0.085)	0.034(0.043)	0.104(0.061)	1.745	.478	10.99	0.911	18.0	1997 Feb. 12
1992 TC	18.3	–	0.046(0.084)	-0.35 (0.19)	1.566	.292	7.09	1.108	18.0	1997 Jan. 10
3362*	19.0	–	-0.05 (0.15)	0.05 (0.19)	0.989	0.469	9.90	0.525	18.1	1996 Oct. 15,17
1996 FG3*	17.6	-0.12 (0.11)	-0.072(0.061)	-0.129(0.088)	1.054	.350	1.98	0.686	18.5	1997 Feb. 12
4947*	16.8	0.299(0.081)	0.048(0.028)	0.076(0.039)	1.370	0.168	15.66	1.140	18.5	1996 Ott 13,15,16
1996 RG3	18.6	–	-0.18 (0.13)	-0.09 (0.13)	2.006	0.606	3.61	0.790	18.5	1996 Ott 14,15,16
1996 TR6*	18.9	–	0.17 (0.15)	0.46 (0.16)	1.572	0.176	21.90	1.295	18.5	1996 Oct. 14,17
1996 TA9	19.0	–	-0.075(0.095)	0.05 (0.12)	2.822	0.523	12.30	1.346	19.5	1996 Oct. 13,14,15
1996 TE9*	17.7	–	0.132(0.031)	0.154(0.036)	1.656	0.278	20.43	1.196	19.5	1996 Oct. 14,15,16
1996 PH2	18.3	–	-0.18 (0.12)	-0.34 (0.13)	2.115	.380	13.91	1.311	20.0	1996 Aug. 15
1996 TQ6	19.8		0.81 (0.38)	-0.13 (0.55)	2.310	0.408	6.04	1.368	20.5	1996 Oct. 14
1996 TD9*	19.2	–	-0.10 (0.15)	-0.28 (0.21)	1.332	0.404	5.05	0.794	24.0	1996 Oct. 15,17

Figure Captions

Figure 1. Reflectance colors, V-I vs V-R, for Earth approaches observed at TMO: (a) $H < 17$ ($d > \sim 2$km) and (b) $H \geq 17$ ($d < \sim 2$km). Large triangles represent asteroids only observed in V, R, and I, and large, filled squares represent the subset of bodies also observed in B (see Fig. 2). Small x's, squares, and 3-pointed stars respectively represent main-belt asteroids of type C, S, and D observed during the Eight Color Asteroid Suvey [18]. Large stars with 4, 5, 6, 7, and 8 points show the reflectance colors for L4, L5, L6, H6, and LL6 ordinary chondrites, respectively [2].

Figure 2. Reflectance colors, B-V vs V-R, for Earth approaches observed at TMO: (a) $H < 17$ ($d > \sim 2$km) and (b) $H \geq 17$ ($d < \sim 2$km). See Fig. 1 for symbol explanations.

Figure 3. Reflectance colors, V-I vs V-R, for Earth approaches observed at TMO (open and filled boxes for $a < 2.3$ AU and $a \geq 2.3$ AU, respectively).

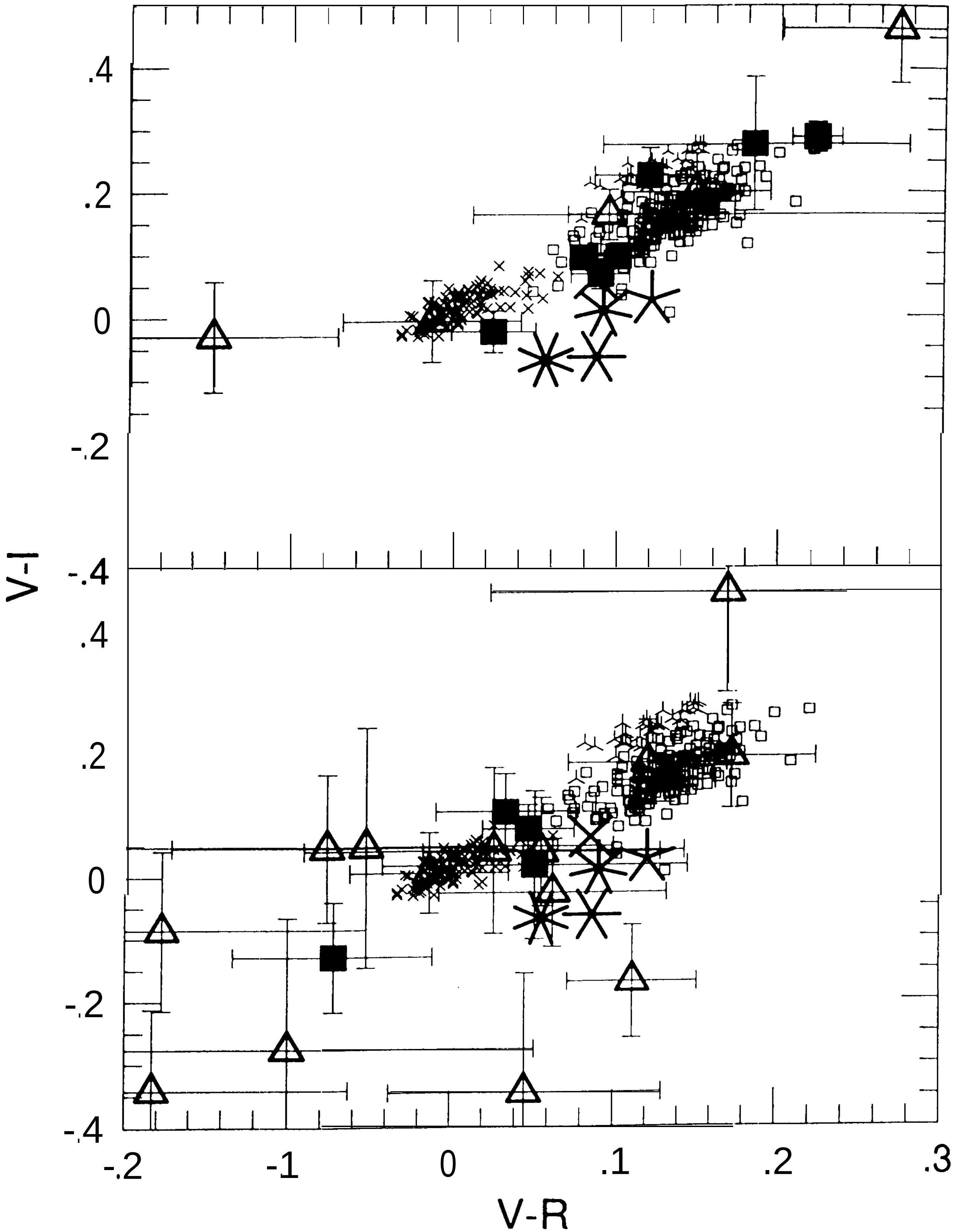

Fig. 1

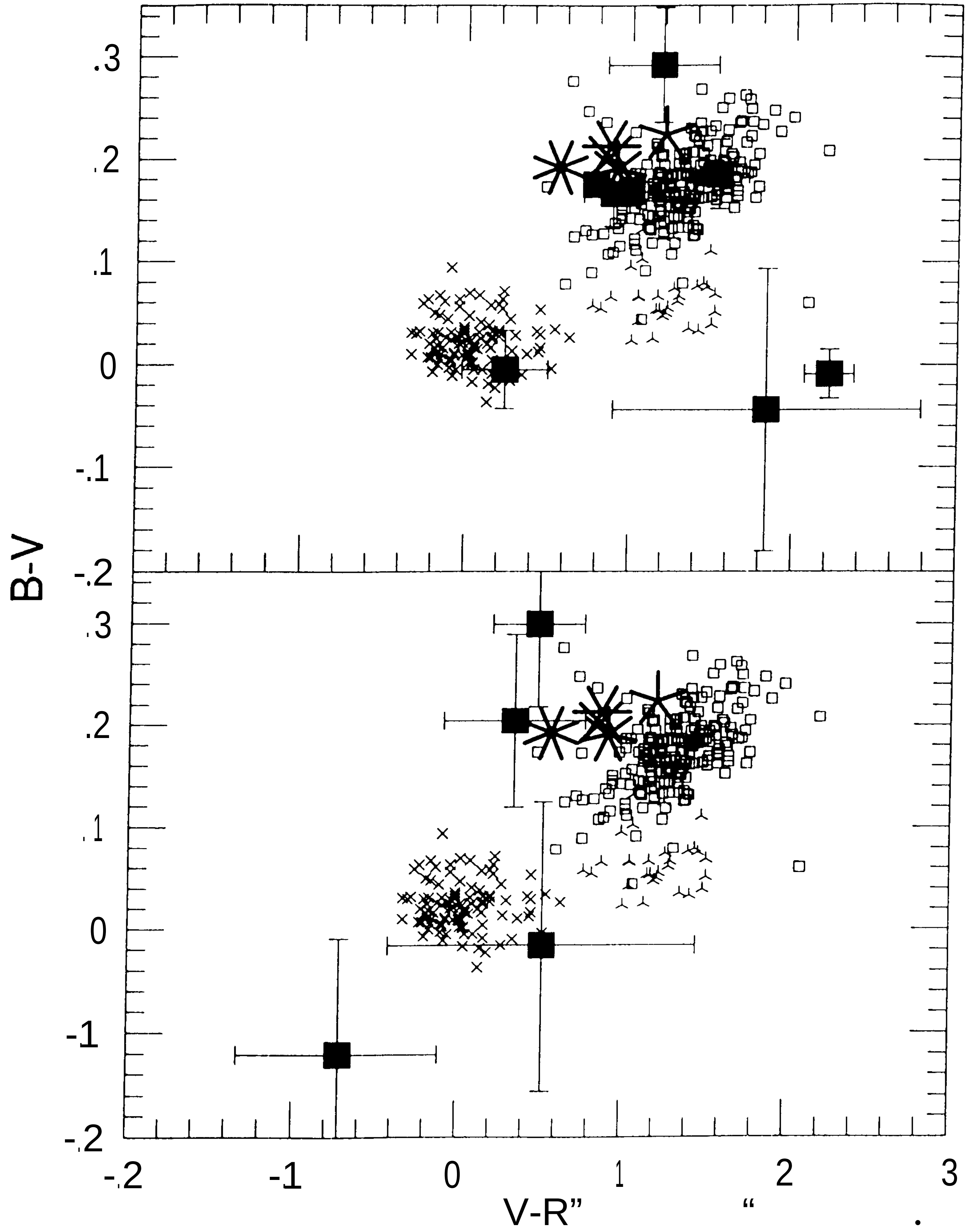

Fig. 2

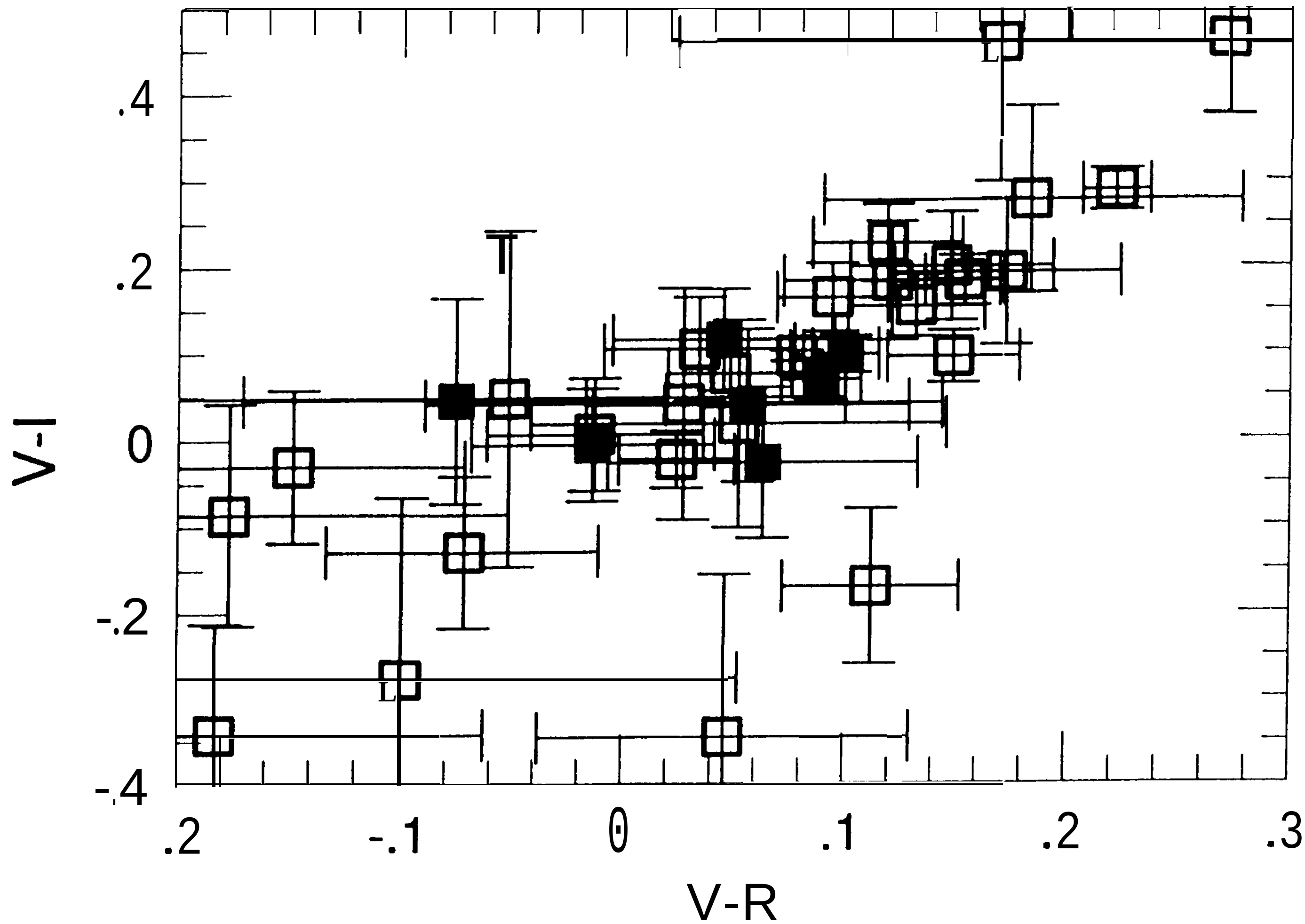

Fig. 3